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Statistical Evaluation of a New Resistance Model for Cold-formed Stainless Steel Cross-sections Subjected to Web Crippling

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Abstract

This paper presents a statistical evaluation according to Annex D of EN 1990 (2002) of a new resistance function for web crippling design of cold-formed stainless steel cross-sections. This resistance function was derived by Bock *et al.* (2013) through the use of carefully validated numerical models with the aim to propose a design expression for stainless steel sections, which are currently designed following the provisions for cold-formed carbon steel sections given in EN 1993-1-3 (2006). Although it was shown that the proposed design equation is appropriate for application to various stainless steels, the statistical uncertainties in material properties that the different types of stainless steels exhibit require an assessment of various partial safety factors. The statistical assessment showed that the proposed resistance function by Bock *et al.* (2013) requires adjustment to satisfy the safety level set out in EN 1993-1-4 (2006); A recalibration is performed herein. The web crippling design provisions given in EN 1993-1-3 (2006) and SEI/ASCE 8-02 (2002) American standard for application to stainless steel are also statistically evaluated herein. Comparison with test and numerical data showed that the predictions of the recalibrated resistance function are better suited and consistent than existing design provisions.

Keywords: cold-formed sections, concentrated loads, numerical analyses, stainless steel, statistical validation, web crippling

1. Introduction

Cold-formed members exhibit a high strength-to-weight ratio which makes them attractive for a variety of structural applications where the use of less material has profound financial and environmental benefits. In particular, cold-formed stainless steel members possess the additional advantages of excellent corrosion resistance and recyclability which may offset the disadvantage of high material cost when cost is considered on a whole life basis. However, high slenderness of cold-formed member makes them more susceptible to local instabilities such as web crippling where the cross-section becomes unstable under concentrated transverse forces. The web crippling design equations given in existing structural design guidance take into account the type of loading and load location. Forces applied through one side of the cross-section flange are defined as one-flange loading, while those acting on both cross-section flanges are defined as two-flange loading. Depending on the location of the load, distinction is made between interior and exterior loading if the load is applied within the span or at the end of the member, respectively. The combination of these situations defines the four loading cases: IOF (interior one-flange), ITF (interior two-flanges), EOF (exterior one-flange) and ETF (exterior two-flanges). This classification is currently adopted in SEI/ASCE 8-02 (2002) American standard for application to stainless steel while the design expressions given in EN 1993-1-3 (2006) use relevant categories. Category 1 is the EOF, ETF and ITF counterpart while Category 2 is equivalent to IOF loading.

Web crippling is a complex type of local failure because it includes a large number of factors. Because of this, most existing expressions for web crippling design are empirical in nature and were calibrated by statistical fitting against experimental data. Winter and Pian (1946) proposed the first curve-fitting expression for carbon steel I-sections under EOF and IOF loading at Cornell University. After that, many empirical equations have been derived and implemented in the design rules for other cross-section geometries and load cases. Relevant research includes the studies performed by Baehre (1975), Hetrakul and Yu (1978), Wing (1981), Packer (1984), Santaputra *et al.* (1989), Studnicka (1990), Bhakta *et al.* (1992), Prabhakaran (1993), Cain *et al.* (1995), and Gerges (1997). In parallel

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with these studies on carbon steel, research was also conducted by Tsai (1987), Bakker and Stark (1994), Zhao and Hancock (1992, 1995), Hofmeyer *et al*. (2001) and Young and Hancock (2001) where analytical models for various types of cross-sections are proposed.

Given the new usage of stainless steel in construction and the urge to provide practising engineers and researchers with design rules, the first version of the current SEI/ASCE 8-02 (2002) American standard for stainless steels, the ANSI/ASCE 8-90 (1991) American standard, adopted the web crippling design provisions for carbon steel. The suitability of this assumption was assessed by Korvink *et al*. (1995) in the Rand Afrikaans University, where some discrepancies were observed.

The aim of following studies was therefore to achieve better understanding of the effect of material behaviour on web crippling response and to develop appropriate design provisions for stainless steels. While research conducted by Zhou and Young (2006, 2007a, 2007b, 2007c, 2008) focused on the development of web crippling design expressions within the framework of SEI/ASCE 8-02 (2002) American standard and NASPEC-2001 (2001) specifications, Talja and Salmi (1995), Talja (2004), Zilli (2004) and Bock *et al*. (2013), among other studies, assessed the European code. It is within this latter research, where a new expression adapted from EN 1993-1-3 (2006) was proposed to predict the web crippling resistance of cold-formed stainless steel members. The studied cross-sections were cold-formed square hollow sections (SHS), rectangular hollow sections (RHS) and hat sections. The purpose of this paper is to conduct a statistical evaluation according to Annex D of EN 1990 (2002) to assess the reliability of the proposed design equation by Bock *et al*. (2013) and provide a safe equation, where recalibration is required, applicable to various stainless steel grades.

2. Existing Design Guidance

2.1. European design rule EN 1993-1-3

The web crippling design rules for stainless steel cross-sections given in EN 1993-1-4 (2006) are adopted from the specifications for cold-formed carbon steel members provided by EN 1993-1-3 (2006). The current design approach given in EN 1993-1-3 (2006) to determine the web crippling cross-section design resistance per web $R_{w,Rd}$ provides various empirical equations for various load cases (relevant categories) and takes into consideration the number of webs of the cross-section as well as whether they are stiffened or unstiffened. For the case of cross-sections with two or more unstiffened webs, which the proposed equation by Bock *et al*. (2013) deals with, the resistance is given by Eq. (1) where r is the internal radius of the corners, t is the thickness, ϕ is the relative angle between the web and the flange, E is the material Young's modulus and $\sigma_{0.2}$ is the material proof strength. The equation also depends on α and l_a, which are a non-dimensional coefficient related to the cross-section geometry and the effective bearing length related to the relevant category, respectively. The values of these parameters for hat sections are given in EN 1993-1-3 (2006) as follows: for Category 1 (EOF) $\alpha = 0.057$ and $l_a = 10$ mm; for Category 2 (IOF) $\alpha = 0.115$ and $l_a = s_s$ where s_s is the bearing length over which the transversal load is applied. The design formulation includes a partial safety factor γ_{M1}. Despite EN 1993-1-3 (2006) does not explicitly give design rules for the determination of the web crippling resistance for SHS and RHS, Talja and Salmi (1995) proposed to assume coefficients for sheeting with values of $\alpha = 0.075$ for Category 1 (EOF) and $\alpha = 0.15$ for Category 2 (IOF). This is therefore adopted in the present study; previous investigations have also used this approach (Gardner *et al*. (2006), Talja and Hradil (2011) and Bock *et al*. (2013)).

$$R_{w,Rd} = \alpha t^2 \sqrt{\sigma_{0.2} E}\left(1-0.1\sqrt{\frac{r}{t}}\right)\left(0.5+\sqrt{\frac{0.02 l_a}{r}}\right)\left(2.4+\left(\frac{\phi}{90}\right)^2\right)/\gamma_{M1} \tag{1}$$

In addition, those cross-sections subjected to the combined action of a bending moment M_{Ed} and a transverse force R_{Ed} (i.e. interior supports of continuous spans - IOF or Category 2) should satisfy Eqs. (2)-(4) where $M_{c,Rd}$ is the moment resistance of the cross-section and $R_{w,Rd}$ is the sum of the local transverse resistances of the individual webs as given by Eq. (1). The web crippling cross-section design resistance for elements under such combination of actions $R_{WC\text{-}BD}$ is given by Eq. (5) where L and s_{sL} are defined in Fig. 1.

$$\frac{R_{Ed}}{R_{w,Rd}} \le 1 \tag{2}$$

$$\frac{M_{Ed}}{M_{c,Rd}} \le 1 \tag{3}$$

$$\frac{R_{Ed}}{R_{w,Rd}} + \frac{M_{Ed}}{M_{c,Rd}} \le 1.25 \tag{4}$$

$$R_{WC\text{-}BD} = R_{Ed} = 1.25/\left(\frac{1}{R_{w,Rd}} + \frac{L-s_{sL}}{4M_{c,Rd}}\right) \le min\{R_{Ed}, 4M_{c,Rd}/(L-s_{sL})\} \tag{5}$$

2.2. SEI/ASCE 8-02 American standard

In the American framework, SEI/ASCE 8-02 (2002) provides Eq. (6) and (7) for web crippling design of shapes having single webs and unstiffened flanges, upon which the proposed equation by Bock *et al*. (2013) is concerned, under IOF loading while for EOF loading, the expression is given in Eq. (8). In these equations, the coefficients C_1, C_2, C_3, C_4 and C_θ are defined in Eqs. (9)-(13). Bending and web crippling interaction effects are accounted for as given by Eq. (14) which may be rewritten as Eq. (15), where $\phi_w = 0.7$ and $\phi_b = 0.85$ are the resistance factor for web crippling and bending, respectively. For consistency reasons, the above mentioned expressions follow EN 1993-1-3 (2006) symbols and SI units.

$$R_{w,Rd} = 6.9\phi_w t^2 C_1 C_2 C_\theta\left(538-0.74\frac{h}{t}\right)\left(1+0.007\frac{s_s}{t}\right)$$

$$\text{if } \frac{s_s}{t} \leq 60 \tag{6}$$

$$R_{w,Rd} = 6.9\phi_w t^2 C_1 C_2 C_\theta\left(538-0.74\frac{h}{t}\right)\left(0.75+0.011\frac{s_s}{t}\right)$$

$$\text{if } \frac{s_s}{t} > 60 \tag{7}$$

$$R_{w,Rd} = 6.9\phi_w t^2 C_3 C_4 C_\theta\left(244-0.57\frac{h}{t}\right)\left(1+0.01\frac{s_s}{t}\right) \tag{8}$$

$$C_1 = \left(1.22-0.22\frac{f_{yb}}{227.7}\right)\frac{f_{yb}}{227.7} \text{ if } \frac{f_{yb}}{631.35} \leq 1 \text{ or}$$

$$C_1 = 1.69 \text{ if } \frac{f_{yb}}{631.35} > 1 \tag{9}$$

$$C_2 = \left(1.06-0.06\frac{r}{t}\right) \leq 1\text{i} \tag{10}$$

$$C_3 = \left(1.33-0.33\frac{f_{yb}}{227.7}\right)\frac{f_{yb}}{227.7} \text{ if } \frac{f_{yb}}{458.85} \leq 1 \text{ or}$$

$$C_3 = 1.34 \text{ if } \frac{f_{yb}}{458.85} > 1 \tag{11}$$

$$C_4 = \left(1.15-0.15\frac{r}{t}\right) \leq 1 \text{ but not less than 0.50} \tag{12}$$

$$C_\theta = 0.7+0.3(\phi/90)^2 \tag{13}$$

$$\frac{1.07R_{Ed}}{\phi_w R_{w,Rd}} + \frac{M_{Ed}}{\phi_b M_{c,Rd}} \leq 1.42 \tag{14}$$

$$R_{WC\text{-}BD} = R_{ED} =$$

$$1.327/\left(\frac{1}{\phi_w R_{w,Rd}} + \frac{L-s_{sL}}{4\phi_b M_{c,Rd}}\right) \leq min\{F_{Ed}, 4M_{c,Rd}/(L-s_{sL})\} \tag{15}$$

3. Summary of the Proposed Web Crippling Resistance Function for Stainless Steel Cross-sections

The investigation conducted by Bock *et al*. (2013) examined numerically the web crippling response of ferritic and austenitic stainless steel SHS, RHS and hat sections using the finite element software ABAQUS. In the study, the load cases under consideration were internal and external concentrated loads applied through one flange, IOF and EOF respectively. It is note worthy that this load cases resemble the web crippling response of continuous spans where the local transverse forces satisfy IOF loading (Category 2) at interior supports while EOF loading (Category 1) is given at the end of the member as shown in Fig. 1, where these forces are denoted as s_{sL} for the former and s_{sa} for the latter. The obtained models, which had been validated against existing experimental results conducted by Talja and Hradil (2011), were used to analyse key parameters influencing the web crippling resistance. Comparisons presented by Bock *et al*. (2013) with numerical and test data, highlighted the over conservative predictions of EN 1993-1-3 and showed that some modifications of the original formula given in the code could improve the predicted strength. Upon this observation, three main changes were proposed: the inclusion of the 1% proof strength $\sigma_{1.0}$ in order to consider the strain hardening of stainless steel, some adjustments of the corner radius and the bearing length influence, and three non-dimensional coefficients (β, δ and ξ) were added to obtain better fit with numerical data (see Table 1). The proposed resistance model is given by Eq. (16) where $k = \delta r / t$ and $l_a = 0.01s_s$ for EOF (or Category 1) while for IOF (or Category 2), $l_a = 2.2s_s$. Predictions by this proposed resistance model were observed to provide more accurate web crippling resistances than EN 1993-1-3 (2006) enabling a more efficient design. Furthermore, the expression was observed to be suitable for application to both types of stainless steel: austenitic and ferritic stainless steels.

$$R_{w,Rd} = \alpha t^2\sqrt{\sigma_{0.2}E}\left(\xi\frac{\sigma_{1.0}}{E}\right)^k\sqrt{\frac{\beta t}{r}}\left(0.5+\sqrt{\frac{0.01l_a}{t}}\right)\left(2.4+\left(\frac{\phi}{90}\right)^2\right)/\gamma_{M1} \tag{16}$$

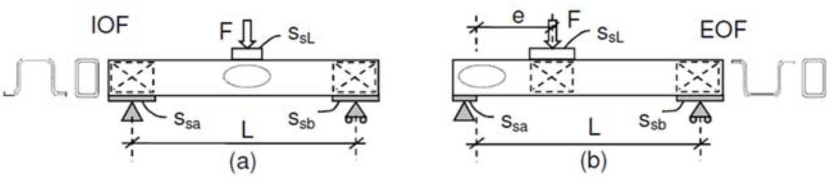


Figure 1. Loading cases considered: (a) interior one-flange (IOF or Category 2) and (b) exterior one-flange (EOF or Category 1).

Table 1. Non-dimensional coefficient values

Coefficient	Category 1 (EOF)		Category 2 (IOF)	
	SHS/RHS	Hat sections	SHS/RHS	Hat sections
α	0.07	0.085	0.13	0.14
β	2.14	1.65	0.59	0.81
δ	0.22	0.13	0.14	0.065
ξ	2200	2275	2700	2000

4. Statistical analysis

4.1. Annex D of EN 1990

When an alternative design rule is proposed, the resulting design model r_t for the resistance function grt ($\underline{X}_m$), where $\underline{X}_m$ refers to all basic variables (i.e. geometry, mechanical material properties and non-dimensional coefficients) that affect the resistance at the relevant limit state, should be in accordance with the principles of EN 1990 (2002). Annex D of EN 1990 (2002) establishes the principles for design assisted by testing, where the reliability of the derived model is assesses on the basis of a statistical interpretation of available test data. The standard evaluation procedure given in Annex D of EN 1990 (2002) considers two methods to statistically evaluate a design model: Method a) by evaluating the characteristic value of the resistance function r_k; and Method b) by direct determination of the design value of the resistance function r_d. Hence, the partial safety factor can be obtained dividing the characteristic value by the design value as given by Eq. (17).

$$\gamma_{M1} = \frac{r_k}{r_d} \tag{17}$$

Both methods are given in Annex D of EN 1990 (2002) as a number of discrete steps which are summarised in Table 2. It is important to mention that the basic variables X_i (related to material and geometry) for evaluating the design and characteristic resistance functions, r_d and r_k respectively, are based on different values. While the material mechanical properties are defined as nominal values ($\sigma_{0.2\ \mathrm{nom}}$), which could be understood as the minimum (characteristic) value to be satisfied after the steelmaking with an over-strength ratio M_{osr} (average difference between the true strength of the material and the value used in design), the nominal geometrical values are adopted as mean values with a certain fabrication tolerance. To statistically harmonise these discrepancies and use nominal values for all input parameters, EN 1990 introduces the nominal resistance function r_n to correct the partial safety factor γ_{M1} into γ^*_{M1}. The nominal value of this resistance function r_n is determined evaluating the resistance function using the nominal values for the basic variables (i.e. measured value for the geometry and $\sigma_{0.2\ \mathrm{nom}} = \sigma_{0.2}/M_{osr}$ for the material where $\sigma_{0.2}$ is the measured value of the 0.2% proof strength). Baddoo and Francis (2012, 2013) undertook a large collection of data from steel producers and manufacturers where the overstrength ratio M_{osr} was found to be 1.3, 1.2 and 1.1 for austenitic, ferritic and duplex stainless steel, respectively. The transformed value of γ^*_{M1} is given by Eq. (18) and is used herein to statistically evaluate the proposed resistance function r_t by Bock *et al.* (2013) (Eq. (19)) and existing design standards.

$$\gamma^*_{M1} = \frac{r_k r_n}{r_d r_k} = \frac{r_n}{r_d} \tag{18}$$

$$r_t = g_{rt}(\underline{X}_m) = \alpha t^2\sqrt{\sigma_{0.2}E}\left(\xi\frac{\sigma_{1.0}}{E}\right)^k\sqrt{\frac{\beta t}{r}}\left(0.5+\sqrt{\frac{0.01 l_a}{t}}\right)\left(2.4+\left(\frac{\phi}{90}\right)^2\right) \tag{19}$$

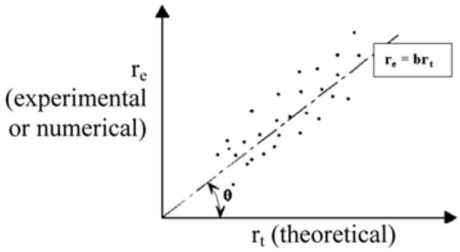
4.2. Adaptation of the procedure to a numerical database

The original procedure given in Annex D of EN 1990 (2002) is intended to statistically evaluate resistance functions (design models) derived through the use of experimental data r_e (experimental). Due to the fact that the statistical evaluation performed in this study is based on numerical results, r_e (numerical), an additional term V_{FEM} was considered for the combined coefficient of variation V_r^2 as given by Eq. (20).

$$V_r^2 = V_\delta^2 + V_{rt}^2 + V_{FEM}^2 \tag{20}$$

This V_{FEM} term refers to the coefficient of variation of the numerical model and was proposed to be included in V_r^2 by Davaine (2005) to consider uncertainties and unfavourable deviations between the numerical model and the experimental data considered for its calibration; this approach has also been used by Gabeler (2009) and Chacón *et al.* (2012) in their studies on plate girders subjected to patch loading. The proposed process by Davaine (2005) to determine the value of V_{FEM} is given in the set of Eqs. (21)-(26) where $r_{e,i}$ are experimental values, $r_{FEM,i}$ are their corresponding numerical values predicted by the numerical model, b_{FEM} is the average ratio of experimental to numerical based on a least squares fit to the test data, $\delta_{FEM,i}$ is the error term for each numerical value, n_{FEM} is the population of numerical analyses taken under consideration and $r_{FEM,i}$, $\Delta_{FEM,i}$, $\overline{\Delta}_{FED}$ and $s^2_{\Delta,FED}$ are statistical parameters. Note that this notation resembles the one used to determine the coefficient of variation of the error V_δ (see Table 2).

Table 2. Summary of the discrete steps

Step	Feature	Objective
1. Develop a design model	$r_t = g_{rt}(\underline{X}_m)$	Develop a design model for the theoretical resistance r_t represented by the resistance function $r_t = g_{rt}(\underline{X}_m)$ and to consider all the basic variables X_i through the vector $\underline{X}_m = \Sigma_{i=1}^{m} X_i$, where m is the number of the various basic variables (i.e. geometry, material, coefficients)
2. Compare experimental (or numerical) and theoretical values	 	See and study the deviation of all the experimental (or numerical) $r_{e,i}$ and their corresponding theoretical values $r_{t,i}$. If the resistance function is exact and complete, the points will lie on the line $\theta=\pi/4$, but in practice the points show some scatter. The vectors $r_{e,i}$ and $r_{e,t}$ must have the same dimension n (population of data taken under consideration)
3. Estimate the mean value of the correction factor b	$b = \dfrac{\Sigma_{i=1}^{n} r_e r_t}{\Sigma_{i=1}^{n} r_t^2}$	Represent the probabilistic model of the resistance r in the format $r = br_{t,i}\delta$, where b is the least squares best-fit to the slope and δ is the error term
4. Estimate the coefficient of variation V_δ of the δ_i error terms	$\delta_i = \dfrac{r_{e,i}}{br_{t,i}}$ $\quad \bar{\Delta} = \dfrac{1}{n}\sum_{i=1}^{n}\Delta_i$ $\Delta_i = \ln(\delta_i)$ $\quad s_\Delta^2 = \dfrac{1}{n-1}\sum_{i=1}^{n}(\Delta_i - \bar{\Delta})^2$	Determine the error term δ_i for each experimental (or numerical) value $r_{e,i}$ to estimate the coefficient of variation of the errors from the values of $\Delta_i, \bar{\Delta}$ and s_Δ^2 through $V_\delta = \sqrt{\exp(s_\Delta^2) - 1}$
5. Analyse compatibility	Kolmogorov-Smirnov tests.	Test the normality of the distribution of the errors δ_i
6. Define the coefficients of variation $V_{X,i}$ for the basic variables X_i (material and geometry)	Parameter / Mean X_i / $V_{X,i}$ $M_{osr}\sigma_{0.2}$ for austenitic / $1.3\sigma_{0.2,nom}$ / 0.066 $M_{osr}\sigma_{0.2}$ for ferritic / $1.2\sigma_{0.2,nom}$ / 0.050 $M_{osr}\sigma_{0.2}$ for duplex / $1.1\sigma_{0.2,nom}$ / 0.049 Geometry / nominal value / 0.050	These coefficients of variation $V_{X,i}$ have been recently presented for stainless steel in Baddoo and Francis (2012, 2013) after an extensive statistical study of data collected from the stainless steel suppliers and manufacturers
7. Define the combined coefficient of variation V_r^2	$V_{rt}^2 = \dfrac{var[g_{rt}(\underline{X}_m)]}{g_{rt}^2(\underline{X}_m)} = \dfrac{1}{g_{rt}^2(\underline{X}_m)}\sum_{i=1}^{j}\left[\dfrac{\partial g_{rt}}{\partial X_i}\cdot V_{X,i}\right]^2$ $V_r^2 = V_\delta^2 + V_{rt}^2 + V_{FEM}^2$	This term is considered to include all possible deviations: errors (V_δ), resistance function (V_{rt}^2) and the deviation of the numerical model (V_{FEM}^2) proposed by Davaine (2005) given in sub-section 4.3
8. a. Method a) Definition of the characteristic value	$r_k = bC_k g_{rt}(X_m)$ $C_k = \exp(-k_\infty \alpha_{rt} Q_{rt} - k_n \alpha_\delta Q_\delta - 0,5Q^2)$	$Q_{rt} = \sqrt{\ln(V_{rt}^2 + 1)}$ $\quad Q_\delta = \sqrt{\ln(V_\delta^2 + 1)}$ $Q = \sqrt{\ln(V_r^2 + 1)}$
8. b. Method b) Definition of the design value	$r_d = bC_d g_{rt}(X_m)$ $C_d = \exp(-k_{d,\infty}\alpha_{rt} Q_{rt} - k_{d,n}\alpha_\delta Q_\delta - 0,5Q^2)$	$\alpha_{rt} = \dfrac{Q_{rt}}{Q}$ $\quad \alpha_\delta = \dfrac{Q_\delta}{Q}$ - k_n and k_∞ are defined in Table D1 of EN 1990 while $k_{d,n}$ and $k_{d,\infty}$ are given in Table D2.
9. Partial safety factor	$\gamma_{M1} = \dfrac{r_k}{r_d} = \dfrac{C_k}{C_d}$	The partial safety factor is obtained dividing r_k by r_d
10. Corrected partial safety factor	$\gamma_{M1}^* = \dfrac{r_k r_n}{r_d r_k} = \dfrac{r_n}{r_d}$	To adapt the partial safety factor to better statistical variations

$$b_{FEM} = \frac{\sum r_{e,i} r_{FEM,i}}{\sum r_{FEM,i}^2} \tag{21}$$

$$\delta_{FEM,i} = \frac{r_{e,i}}{b_{FEM} r_{FEM,i}} \tag{22}$$

$$\Delta_{FEM,i} = \ln(\delta_{FEM,i}) \tag{23}$$

$$\bar{\Delta}_{FEM} = \frac{1}{n_{FEM}}\sum_{i=1}^{n_{FEM}} \ln(\delta_{FEM,i}) \tag{24}$$

$$s_{\Delta,FEM}^2 = \frac{1}{n_{FEM}-1}\sum_{i=1}^{n}(\Delta_{FEM,i} - \bar{\Delta}_{FEM})^2 \tag{25}$$

$$V_{FEM} = \sqrt{\exp(s_{\Delta,FEM}^2) - 1} \tag{26}$$

Table 3. Available numerical database

Load case	Cross-Section type	Ferritics	Austenitics
IOF	SHS/RHS	83	53
	Hat sections	74	64
EOF	SHS/RHS	71	41
	Hat sections	34	24
	Total	262	182

5. Numerical Analyses

5.1. Available numerical database

In order to conduct the statistical evaluation of the proposed resistance function given in (Eq (19)), the generated numerical data by Bock *et al.* (2013) was considered and split into sub-sets based on their load condition, cross-section geometry and material. Given the fact that most of the numerical analyses were performed on ferritic stainless steel cross-sections and little numerical data for austenitic stainless steel was available, this latter database is expanded in the present paper on the basis of parametric studies by using the finite element package ABAQUS. Further details of the numerical analyses are given in the following sub-sections. Having complemented the original available numerical data, a total of 262 and 182 numerical results for ferritic and austenitic stainless, respectively, steel were involved in the statistical analysis. Details of the amount of numerical data considered in each sub-set are given in Table 3.

5.2. Parametric study

The additional numerical analyses of the simulations performed by using ABAQUS on austenitic stainless steel cross-sections with material mechanical properties given in Table 4 are described herein. The cross-sections considered were SHS, RHS and hat sections with the dimensions given in Table 5 with reference to symbols shown in Fig. 2. These cross-sections were modelled under IOF and EOF loading. Thicknesses of 2 mm and 4 mm for the SHS and RHS and 1 mm and 2 mm for the hat sections were considered. The length of all the specimens (L) remained constant at 500 mm. The length of the supports (s_{sa} and s_{sb}) for the IOF loading was set to 50 mm while the bearing length through of which the load is applied (s_{sL}) was 25 mm. For the EOF loading, the length of the support that produces web crippling (end bearing support, s_{sa}) was 25 mm whereas for the further end support (s_{sb}) was 50 mm. The load was applied through a plate (s_{sL}), which was 50 mm length, and the distance from its centre to the edge of the end bearing support (e) was 150 mm. All these abovementioned parameters are depicted in Fig. 1. 4-point bending models were also performed on these geometries to determine the moment resistance of the cross-section $M_{c,Rd}$ and study the combined bending and web crippling interaction effects for IOF loading (Eq. 5). In these models, the load was applied through two plates of 50 mm-wide placed at 1/3 and 2/3 of the total length which was set to 1000 mm. Additional specimens were modelled for materials A1* and A2* to study the influence of various parameters on the web crippling strength, including: two more corner radii (r_m=4 mm and 5 mm for S5, S6, S7 and S9 and r_m=5 mm and 6 mm for S8); four more bearing lengths for IOF loading

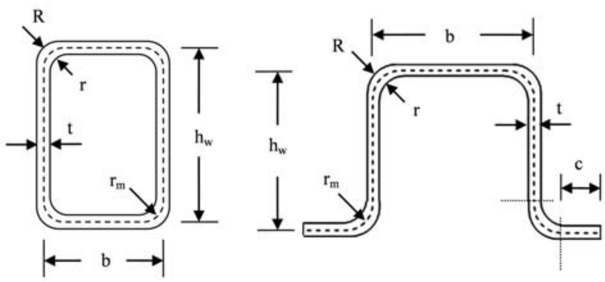


Figure 2. Definition of symbols for the cross-sections.

Table 4. Material mechanical properties considered

Material	E_0 (GPa)	$\sigma_{0.2}$ (MPa)	n	$\sigma_{1.0}$ (MPa)	σ_u (MPa)	m	ε_u	$\sigma_u/\sigma_{0.2}$
A1	200	250	5	256	275	3	0.4	1.1
A1*	200	250	5	262.2	300	3	0.4	1.2
A2	200	250	5	275	350	3	0.4	1.4
A2*	200	250	5	300	450	3	0.4	1.8

Table 5. Basic cross-section geometries considered

Cross-section	Label	b (mm)	h_w (mm)	c (mm)	r_m (mm)
SHS 70×70×t	S5	70	70	-	3
RHS 60×120×t	S6	60	120	-	3
Hat 60×60×20×t	S7	60	60	20	3
Hat 120×120×50×t	S8	120	120	50	3
Hat 60×80×25×t	S9	60	80	25	3

(s_{sL}=40 mm, 50 mm, 75 mm and 100 mm); and four more end bearing lengths (s_{sa}=40 mm, 50 mm, 75 mm and 100 mm) and two plate lengths over which the load is applied (s_{sL}=75 mm and 100 mm) for EOF loading. A total of 44 and 64 numerical analyses were performed on austenitic SHS/RHS and hat sections under IOF loading respectively, while for EOF loading the number of conducted numerical analyses were 31 and 24 for SHS/RHS and hat sections, respectively. Further details of the numerical model used herein are given in Bock *et al*. (2013) where a carefully validation against experimental results was also undertaken. Recall that the parametric study performed herein on austenitic stainless steel cross-section complements the numerical data reported in Bock *et al*. (2013) where more focus was given to the web crippling response of ferritic stainless steel cross-sections. The document also reports an assessment of the sensitivity of the numerical model to different key modelling parameters including initial imperfections and mesh studies as well as the influence of various geometries and material properties on the web crippling response.

The obtained numerical results of this parametric study performed on austenitic stainless steel cross-sections are presented in Appendix A where all the specimens were labelled following the same criteria used by Bock *et al.* (2013) so that the austenitic counterpart result could be compared with the ferritic one.

6. Results of the Statistical Evaluation

6.1. General

In this section, the obtained partial safety factors for the eight sub-sets of considered data (2 load conditions, 2 types of cross-section and 2 materials shown in Table 3) and key results for the steps summarised in Table 2 are analised and used to assess the reliability of the proposed resistance function by Bock *et al*. (2013). The equations given in EN 1993-1-3 (2006) and SEI/ASCE 8-02 (2002) were also considered in this statistical analysis for comparison purposes.

6.2. Estimation of V_{FEM}

The coefficient of variation of the numerical model V_{FEM} was determined preceding the actual statistical analyses since, as mentioned earlier, the data under consideration was based on numerical results. To this end, the results from the validation of the numerical model given by Bock *et al*. (2013), where existing test performed by Gardner *et al*. (2006) and Talja and Hradil (2011) were collected and modelled by using ABAQUS, were considered to determine such parameter. The results are shown in Table 6 where $r_{e,i}$ and $r_{FEM,i}$ are the reported values in the corresponding documents for the experimental and numerical web crippling strength of the cross-section respectively, and b_{FEM}, $\delta_{FEM,i}$, $\Delta_{FEM,i}$, $\overline{\Delta}_{FEM}$ and $s^2_{\Delta,FEM}$ are key statistical parameters determined according to Eqs. (21)-(26).

6.3. Resulting partial safety factors

The obtained partial safety factors from the statistical evaluations are presented herein. The structural design guidance for stainless steels, the EN 1993-1-4 (2006), employs a partial safety factor γ^*_{M1} of 1.1. Hence, partial safety factors falling below this value of 1.1 reflect that the resistance function is reliable. Above 1.1, the design approach is deemed to be unsafe thereby requiring a recalibration so that the safety level is satisfied.

Table 7 and 8 show key results of the statistical evaluation for IOF and EOF loading respectively, while Fig. 3 and Fig. 4 show the numerical resistances r_e plotted against

Table 6. Determination of the V_{FEM}

Type of load	Specimen	$r_{e,i}$ (kN)	$r_{FEM,i}$ (kN)	$r_{e,i}/r_{FEM,i}$	$r_{e,i}r_{FEM,i}$	$r_{FEM,i}^2$	$\delta_{FEM,i}$	$\Delta_{FEM,i}$	$(\Delta_{FEM,i}-\overline{\Delta}_{FEM})^2$
EOF	SHS_ES[a]	25.76	35.36	0.73	910.9	1250.3	0.671	-0.399	0.1241
	TH_10_ES[a]	7.16	7.03	1.02	50.3	49.4	0.939	-0.063	0.0003
	TH_15_ES[a]	15.03	15.07	1.00	226.5	227.1	0.919	-0.084	0.0015
	TH_20_ES[a]	25.91	25.82	1.00	669.0	666.7	0.925	-0.078	0.0010
	TH_30_ES[a]	42.06	39.93	1.05	1679.5	1594.4	0.971	-0.030	0.0003
IOF	SHS_IS[a]	43.92	37.02	1.19	1625.9	1370.5	1.093	0.089	0.0183
	SHS_ 100×100×3[b]	107.10	101.18	1.06	10836.4	10237.4	0.975	-0.025	0.0005
	SHS_120×80×3[b]	108.30	96.42	1.12	10442.3	9296.8	1.035	0.034	0.0065
	RHS_140×60×3[b]	107.50	95.69	1.12	10286.7	9156.6	1.035	0.035	0.0065
	TH_10_IS[a]	10.00	9.75	1.03	97.5	95.1	0.945	-0.056	0.0001
	TH_15_IS[a]	20.73	19.59	1.06	406.1	383.8	0.975	-0.025	0.0004
	TH_20_IS[a]	34.84	32.41	1.07	1129.2	1050.4	0.991	-0.009	0.0013
	TH_30_IS[a]	55.01	50.09	1.10	2755.5	2509.0	1.012	0.012	0.0034
					b_{FEM} = 1.085		$\overline{\Delta}_{FEM}$ = -0.046		$s^2_{\Delta,FEM}$ = 0.014 =
							V_{FEM} = 0.117		

[a] Talja and Hradil (2011)
[b] Gardner *et al*. (2006)

Table 7. Summary of statistical evaluation of various approaches for IOF loading

Material	Cross-section	Design approach	V_δ	V_r	γ_{M1}	γ_{M1}^*
Ferritic	SHS/RHS	EN 1993-1-3	0.132	0.036	1.194	1.147
		ASCE	0.131	0.036	1.193	1.280
		Proposal	0.070	0.024	1.099	0.928
	Hat sections	EN 1993-1-3	0.102	0.029	1.145	0.899
		ASCE	0.090	0.027	1.126	1.188
		Proposal	0.068	0.023	1.098	0.928
Austenitic	SHS/RHS	EN 1993-1-3	0.122	0.036	1.194	1.131
		ASCE	0.125	0.036	1.199	1.232
		Proposal	0.073	0.026	1.119	0.888
	Hat sections	EN 1993-1-3	0.090	0.029	1.141	0.904
		ASCE	0.095	0.030	1.149	1.134
		Proposal	0.062	0.025	1.105	0.892

Table 8. Summary of statistical evaluation of various approaches for EOF loading

Material	Cross-section	Design approach	V_δ	V_r	γ_{M1}	γ_{M1}^*
Ferritic	SHS/RHS	EN 1993-1-3	0.177	0.050	1.282	0.763
		ASCE	0.273	0.094	1.488	1.120
		Proposal	0.216	0.066	1.361	1.355
	Hat sections	EN 1993-1-3	0.185	0.053	1.323	0.819
		ASCE	0.226	0.070	1.419	1.188
		Proposal	0.190	0.055	1.334	1.388
Austenitic	SHS/RHS	EN 1993-1-3	0.171	0.050	1.294	0.760
		ASCE	0.208	0.064	1.373	0.933
		Proposal	0.202	0.062	1.360	1.263
	Hat sections	EN 1993-1-3	0.217	0.068	1.436	0.907
		ASCE	0.230	0.074	1.470	1.076
		Proposal	0.206	0.064	1.408	1.244

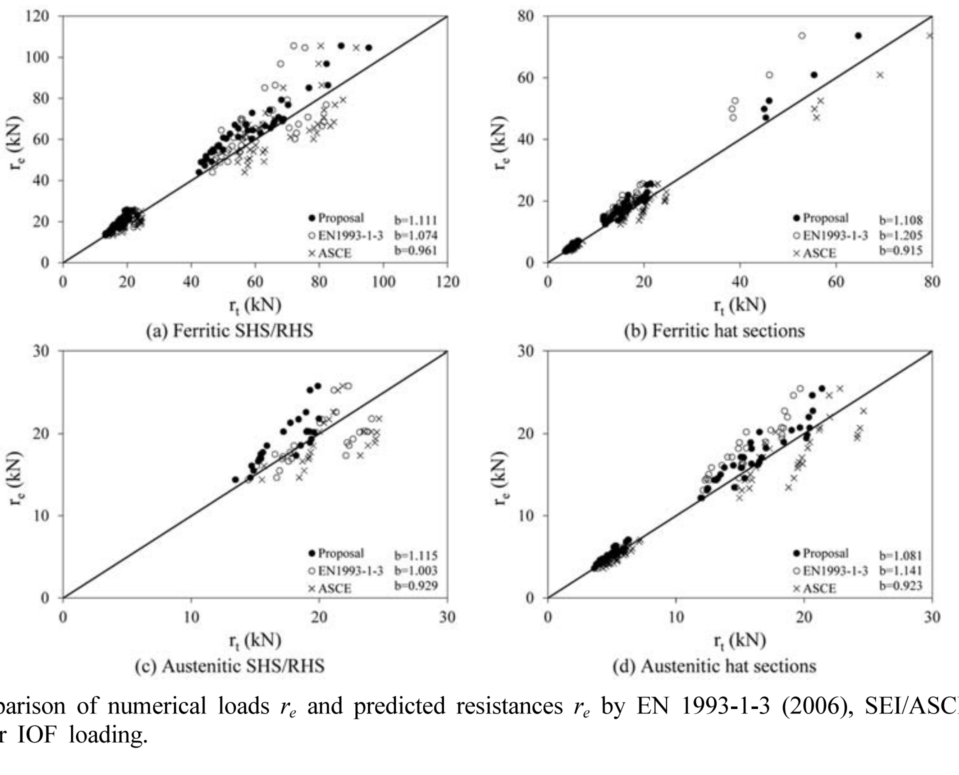


Figure 3. Comparison of numerical loads r_e and predicted resistances r_e by EN 1993-1-3 (2006), SEI/ASCE 8-02 (2002) and proposal for IOF loading.

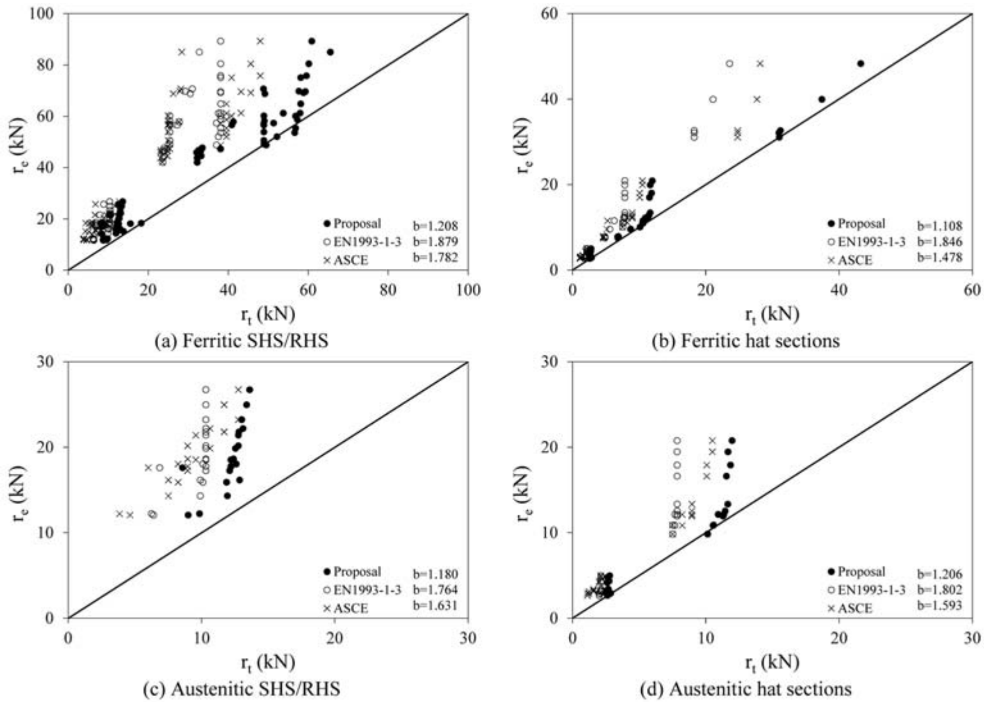


Figure 4. Comparison of numerical loads r_e and predicted resistances r_t by EN 1993-1-3 (2006), SEI/ASCE 8-02 (2002) and proposal for EOF loading.

Table 9. Key statistical values of the comparison for IOF loading

Material	Cross-section	Design approach		Mean	COV
Ferritic	SHS/RHS	EN 1993-1-3	r_e/r_t	1.048	0.133
		ASCE	r_e/r_t	0.958	0.132
		Proposal	r_e/r_t	1.109	0.070
	Hat sections	EN 1993-1-3	r_e/r_t	1.135	0.102
		ASCE	r_e/r_t	0.931	0.090
		Proposal	r_e/r_t	1.101	0.069
Austen-itic	SHS/RHS	EN 1993-1-3	r_e/r_t	1.008	0.120
		ASCE	r_e/r_t	0.938	0.125
		Proposal	r_e/r_t	1.117	0.072
	Hat sections	EN 1993-1-3	r_e/r_t	1.090	0.090
		ASCE	r_e/r_t	0.921	0.095
		Proposal	r_e/r_t	1.078	0.062

Table 10. Key statistical values of the comparison for EOF loading

Material	Cross-section	Design approach		Mean	COV
Ferritic	SHS/RHS	EN 1993-1-3	r_e/r_t	2.007	0.173
		ASCE	r_e/r_t	2.218	0.278
		Proposal	r_e/r_t	1.386	0.225
	Hat sections	EN 1993-1-3	r_e/r_t	1.763	0.193
		ASCE	r_e/r_t	1.822	0.219
		Proposal	r_e/r_t	1.241	0.203
Austenitic	SHS/RHS	EN 1993-1-3	r_e/r_t	1.874	0.168
		ASCE	r_e/r_t	1.906	0.211
		Proposal	r_e/r_t	1.358	0.206
	Hat sections	EN 1993-1-3	r_e/r_t	1.742	0.225
		ASCE	r_e/r_t	1.883	0.216
		Proposal	r_e/r_t	1.287	0.209

the predicted ones r_t for IOF and EOF loading respectively, where the least squares best-fit to the slope b is also given (Step 2 from Table 2). Table 9 show key statistical values concerning mean predictions and coefficient of variation (COV) of the three design approaches relative to the numerical results for IOF loading while for EOF loading, these are given in Table 10. From the results for IOF loading given in Table 7, it can be observed that the proposed resistance function by Bock *et al*. (2013) satisfies the safety level recommended in EN 1993-1-4 (2006) for all sets of data. Note also that this proposal provides higher partial safety factors for ferritic stainless steel than the austenitics reflecting that the former ones are designed more efficiently. EN 1993-1-3 (2006) yields similar partial safety factors for hat sections, though the safety level for SHS and RHS is not satisfied. This is associated with the inaccuracy of the approach to predict web crippling strength for such cross-sections, as is highlighted in Fig. 3(a) and (c) where it is observed that EN 1993-1-3 (2006) over-estimates the resistance of some specimens. Recall that EN 1993-1-3 (2006) does not make allowance for SHS and RHS, and the approach recommended by Talja and Salmi (1995) was used herein. The assessment for SEI/ ASCE 8-02 (2002) shows that this approach is not suitable for the material and cross-sections considered in the present study since the predicted web crippling capacity is too optimistic (see Fig. 3)

Regarding the results for EOF loading, which are given in Table 8, it is observed that the proposed resistance function by Bock *et al*. (2013) yields unreliable predictions for the recommended value γ^*_{M1} of 1.1 given in EN 1993-1-4 (2006). Similar results are observed for the approach given in SEI/ASCE 8-02 (2002) when is applied to ferritic stainless steels, however, the safety level for the austenitics is satisfied. Unlike the results for IOF loading, where some approaches over-estimated web crippling capacities, the unsatisfactory partial safety factors obtained for EOF loading are associated with the high scatter (COV) provided by the actual design approach (see Table 10). Note that, as shown in Fig. 4, the three design methods provide safe values, though the web crippling resistances are overly underestimated as shown the mean prediction given in Table 10. This is also highlighted in the results for the statistical evaluation of EN 1993-1-3 (2006) where all partial safety factors are far below 1.1, but satisfying the safety level. Hence, on the basis of these observations, it is concluded that a revised expression of the proposed resistance function is required for EOF loading. This is conducted in the following section.

6.4. Recalibration of the proposed resistance function

Having concluded that the proposed resistance function for EOF loading requires further adjustment, a revised value for the new non-dimensional coefficient α was sought. This was achieved by setting the corrected partial safety factor γ^*_{M1} for the most restrictive set of data (i.e. ferritic stainless steel SHS and RHS) to the required safety level of 1.1 and limiting the number of decimals of the coefficient α. The coefficients β, δ and ξ were kept since non-significant improvements were observed. The resulting value for α is given in Table 11 together with the coefficients for IOF loading. The results of the statistical evaluation of the recalibrated resistance function for EOF loading are shown in Table 12 where previous resulting partial safety factors for EN 1993-1-3 (2006) and SEI/ASCE 8-02 (2002) are also given. The updated results for the comparison between the numerical resistances r_e and the predicted ones r_t, including the least squares best-fit to the slope parameter b (Step 2 from Table 2), and for the key statistical values concerning mean predictions and coefficient of variation (COV) of the three design approaches relative to the numerical results are given in Fig. 5 and Table 13, respectively. The results show that the recalibrated resistance function satisfies the safety level set out in EN 1993-1-4 (2006). Besides, as it has been observed for IOF loading, higher partial safety

Table 11. Non-dimensional coefficient values after recalibration

Coefficient	Category 1 (EOF)		Category 2 (IOF)	
	SHS/RHS	Hat	SHS/RHS	Hat
α	0.057	0.067	0.13	0.14
β	2.14	1.65	0.59	0.81
δ	0.22	0.13	0.14	0.065
ξ	2200	2275	2700	2000

Table 13. Key statistical values of the comparison for the EOF loading after recalibration

Material	Cross-section	Design approach		Mean	COV
Ferritics	SHS/RHS	EN 1993-1-3	r_e/r_t	2.007	0.173
		ASCE	r_e/r_t	2.218	0.278
		Proposal	r_e/r_t	1.711	0.225
	Hat sections	EN 1993-1-3	r_e/r_t	1.763	0.193
		ASCE	r_e/r_t	1.822	0.219
		Proposal	r_e/r_t	1.571	0.203
Austen-itics	SHS/RHS	EN 1993-1-3	r_e/r_t	1.874	0.168
		ASCE	r_e/r_t	1.906	0.211
		Proposal	r_e/r_t	1.676	0.202
	Hat sections	EN 1993-1-3	r_e/r_t	1.742	0.225
		ASCE	r_e/r_t	1.883	0.216
		Proposal	r_e/r_t	1.629	0.209

Table 12. Partial safety factors for EOF load condition after recalibration

Material	Cross-section	Design approach	V_δ	V_r	γ_{M1}	γ^*_{M1}
Ferritic	SHS/RHS	EN 1993-1-3	0.177	0.050	1.282	0.763
		ASCE	0.273	0.094	1.488	1.120
		Proposal	0.216	0.066	1.361	1.098
	Hat sections	EN 1993-1-3	0.185	0.053	1.323	0.819
		ASCE	0.226	0.070	1.419	1.188
		Proposal	0.190	0.055	1.334	1.097
Austenitic	SHS/RHS	EN 1993-1-3	0.171	0.050	1.294	0.760
		ASCE	0.208	0.064	1.373	0.933
		Proposal	0.202	0.062	1.360	1.023
	Hat sections	EN 1993-1-3	0.217	0.068	1.436	0.907
		ASCE	0.230	0.074	1.470	1.076
		Proposal	0.206	0.064	1.408	0.983

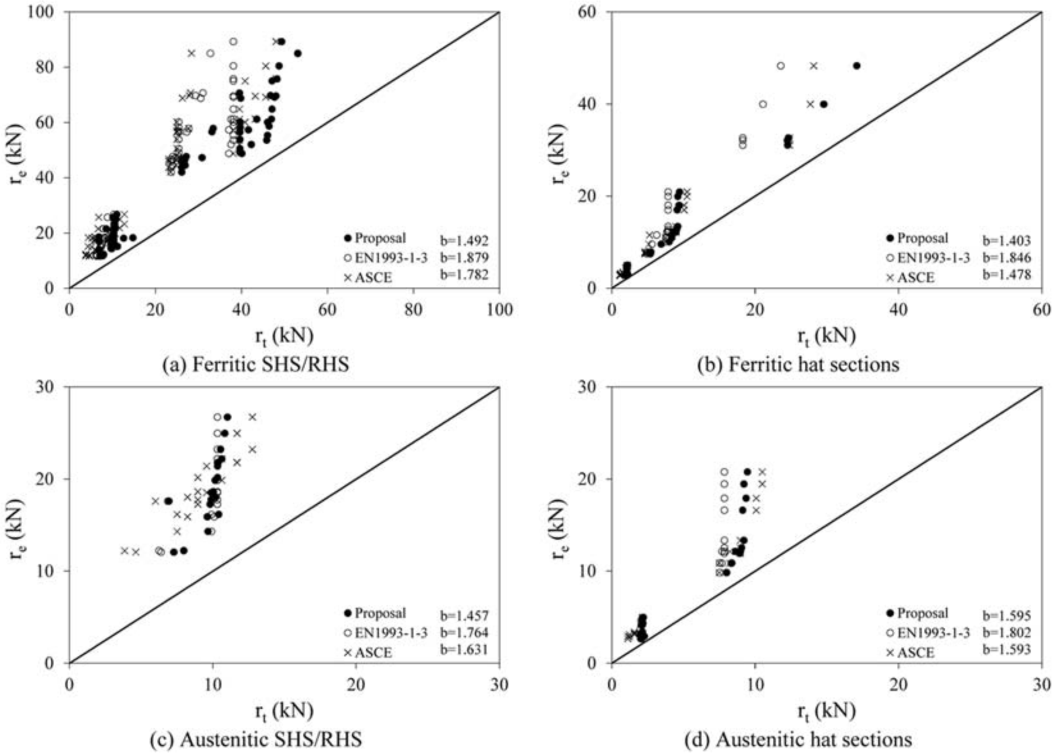


Figure 5. Comparison of numerical loads r_e and predicted resistances r_t by EN 1993-1-3 (2006), SEI/ASCE 8-02 (2002) and proposal for EOF loading after recalibration.

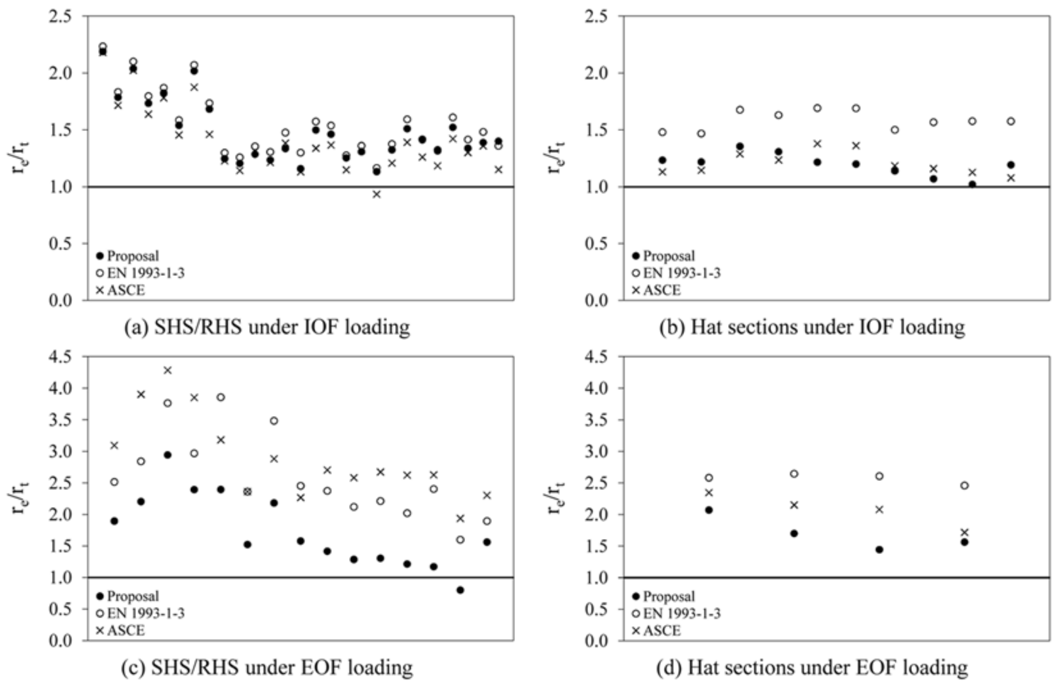


Figure 6. Comparison between the revised resistance function and existing provisions.

Table 14. Statistical results of the ratio r_e/r_t based on experimental results

Load case	Cross-section	Design approach		Mean	COV
IOF	SHS/RHS	EN 1993-1-3	r_e/r_t	1.544	0.179
		ASCE	r_e/r_t	1.404	0.204
		Proposal	r_e/r_t	1.486	0.186
	Hat sections	EN 1993-1-3	r_e/r_t	1.584	0.051
		ASCE	r_e/r_t	1.208	0.081
		Proposal	r_e/r_t	1.194	0.079
EOF	SHS/RHS	EN 1993-1-3	r_e/r_t	2.590	0.250
		ASCE	r_e/r_t	2.884	0.224
		Proposal	r_e/r_t	1.724	0.328
	Hat sections	EN 1993-1-3	r_e/r_t	2.572	0.027
		ASCE	r_e/r_t	2.073	0.110
		Proposal	r_e/r_t	1.694	0.139

factors are achieved for ferritic stainless steels than for the austenitics reflecting that the former ones are designed more efficiently.

7. Validation of the Revised Design Equation with Experimental Results

The predictions of the proposed formulation by Bock *et al*. (2013) and given in Eq. (16) with revised non-dimensional coefficients from Table 11 are compared with existing test results on various stainless steel grades including high strength austenitic and duplex stainless steels (Zhou and Young (2007a, 2007b and 2007c)), austenitic stainless steels (Talja and Salmi (1995) and Gardner *et al*. (2006)) and ferritic stainless steels (Talja and Hradil (2011)). Capacity predictions according to EN 1993-1-3 (2006) and SEI/ASCE 8-02 (2002) are also determined. The comparisons for both load cases are given in Fig. 6 on the basis of the experimental to predicted ratio r_e/r_t where it is observed that the recalibrated resistance function (proposal) achieves a reduction of mean prediction with similar scatter compared to existing design guidance, in line with the observations outlined in sub-sections 6.3 and 6.4 for the numerical data. Key statistical values concerning mean predictions and COV relative to the tests are given in Table 14 for the various sets of data.

8. Conclusions

A statistical evaluation of a proposed resistance model for web crippling design of stainless steel cross-sections under IOF and EOF loading by Bock *et al*. (2013) has been performed according to Annex D of EN 1990 (2002) to determine its level of reliability. Existing design provisions given in EN 1993-1-3 (2006) and SEI/ASCE 8-02 (2002) were also considered for comparison purposes. To this end, parametric studies on austenitic stainless steel were conducted herein to complement the existing numerical data which was considered to derive the proposed resistance model. The available numerical data was split into various sub-sets according to load case (IOF and EOF loading), cross-section geometry (SHS/RHS and hat sections) and material (austenitic and ferritic stainless steel) upon which the assessment of the resulting partial safety factors was based.

The results show that the proposed resistance function satisfies the safety level recommended in EN 1993-1-4 (2006) for IOF loading, but required a readjustment for EOF loading to ensure reliable predictions. A new value for the non-dimensional coefficient α has been proposed. Regarding the assessment of the reliability of existing provisions, SEI/ASCE 8-02 (2002) was observed to be only appropriate for the design of the austenitic set of data under EOF loading generated herein while EN 1993-1-3 (2006) yielded satisfactory results for both load cases, though for IOF loading, the required safety level was not achieved for SHS and RHS.

Predicted web crippling resistances by EN 1993-1-3 (2006), SEI/ASCE 8-02 (2002) and the revised resistance function of numerical data and existing test results on various stainless steel grades showed that the latter provides more accurate predictions enabling a more efficient design for both types of load cases.

Building on the observations regarding the material effect on the partial safety factor and the good agreement achieved between ultimate capacity predictions and existing test results, it is speculated that the proposed formula is also applicable to duplex stainless steel because their stress-tress behaviour lays between the respective values for austenitic and ferritic grades but a formal validation is required.

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Appendix A

Tables A1-A4 present the capacity predictions according to EN 1993-1-3 (2006), SEI/ASCE 8-02 (2002) and proposed resistance model (proposal) of the numerical models generated herein. In these tables, $R_{u,num}$ is the numerical web crippling resistance of the cross-section, $M_{c,num}$ is the numerical bending moment resistance obtained in the 4-point bending model, $R_{w,Rd}$ is the predicted value for the web crippling resistance and $R_{WC\text{-}BD}$ is the combined web crippling and bending strength. All partial safety factors were set to unity to enable a direct comparison.

Specimens were labelled to easily identify load case, material, cross-section and thickness as well as corner radius and bearing length. The first three letters define the load case, where IOF refers to interior one-flange loading and EOF to exterior one-flange loading. The following notation describes the material type (A1, A1*, A2, A2*). The following letter and first number defines the section (S5 to S9). And finally, the value of the thickness (either 1 mm or 2 mm for hat sections and either 2 mm or 4 mm for SHS/RHS). Additional numbers were added when the corner radius or the bearing length that produces crippling (ss_L and ss_a for IOF and EOF loading respectively, with their corresponding values) are varied and the number two is attached when the previously number refers to the variation of the plate length that applies the load (s_{sL}) for EOF loading. The same labels were used by Bock *et al*. (2013) for ferritic stainless steel cross-sections and were adopted herein so that the austenitic counterpart could be compared.

Table A1. Numerical and predicted resistances for SHS/RHS under IOF loading

Specimen		Numerical result		EN1993-1-3		SEI/ASCE 8-02		Proposal	
		$R_{u,num}$ (kN)	$M_{c,num}$ (kNm)	$R_{w,Rd}$ (kN)	$R_{WC\text{-}BD}$ (kN)	$R_{w,Rd}$ (kN)	$R_{WC\text{-}BD}$ (kN)	$R_{w,Rd}$ (kN)	$R_{WC\text{-}BD}$ (kN)
IOF	A1S52	16.94	3.72	25.32	17.09	22.42	19.13	20.84	15.32
IOF	A1S62	18.91	7.40	25.32	22.17	21.61	24.34	20.84	19.27
IOF	A1*S52	17.22	3.76	25.32	17.18	22.42	19.22	20.95	15.43
IOF	A1*S524	15.50	3.72	24.77	16.90	21.73	18.82	19.82	14.87
IOF	A1*S525	14.65	3.695	24.29	16.67	21.04	18.43	19.37	14.63
IOF	A1*S5250	20.24	3.76	30.76	19.00	24.23	20.02	25.39	17.20
IOF	A1*S5275	21.74	3.76	35.04	20.22	26.03	20.76	28.80	18.38
IOF	A1*S52100	25.29	3.76	38.73	21.15	27.84	21.44	31.67	19.28
IOF	A1*S62	19.34	7.46	25.99	22.63	21.61	24.40	20.95	19.38
IOF	A1*S624	18.57	7.38	25.60	22.32	20.95	23.79	19.82	18.55
IOF	A1*S625	17.33	7.33	25.27	22.07	20.28	23.20	19.37	18.20
IOF	A2S52	17.73	3.80	26.52	17.70	22.42	19.33	21.16	15.59
IOF	A2S62	20.16	7.56	26.70	23.15	21.61	24.49	21.16	19.59
IOF	A2*S52	18.53	3.89	26.88	18.02	22.42	19.53	21.55	15.91
IOF	A2*S524	16.96	3.86	26.48	17.83	21.73	19.14	20.58	15.44
IOF	A2*S525	16.64	3.81	26.14	17.59	21.04	18.69	20.30	15.23
IOF	A2*S5250	21.31	3.89	33.12	20.05	24.23	20.35	26.12	17.74
IOF	A2*S5275	22.61	3.89	37.73	21.31	26.03	21.11	29.62	18.96
IOF	A2*S52100	25.78	3.89	41.72	22.27	27.84	21.82	32.58	19.89
IOF	A2*S62	21.82	7.72	28.01	24.09	21.61	24.65	21.55	19.97
IOF	A2*S64	20.24	7.65	27.59	23.77	20.95	24.04	20.58	19.25
IOF	A2*S65	20.30	7.63	27.24	23.54	20.28	23.47	20.30	19.04
IOF	A1S54	53.81	7.92	101.61	48.79	90.99	54.48	87.99	46.06
IOF	A1S64	65.58	15.75	102.32	70.58	89.39	78.43	87.99	64.76
IOF	A1*S54	54.85	8.14	103.04	49.89	90.99	55.42	88.21	46.84
IOF	A1*S544	51.79	8.06	102.24	49.41	90.99	55.05	79.85	44.58
IOF	A1*S545	48.94	7.99	101.6	49.06	89.63	54.47	74.65	43.05
IOF	A1*S5450	60.83	8.14	123.28	53.28	94.81	56.27	103.77	50.03
IOF	A1*S5475	62.71	8.14	138.1	55.33	98.62	57.09	115.71	52.10
IOF	A1*S54100	67.07	8.14	150.91	56.88	102.4	57.86	125.77	53.65
IOF	A1*S64	67.40	16.23	107.47	73.49	89.39	79.50	88.21	65.65
IOF	A1*S644	63.13	16.085	106.64	72.89	89.39	79.18	79.85	61.59
IOF	A1*S645	60.25	15.93	105.99	72.33	88.05	78.19	74.65	58.85
IOF	A2S54	56.81	8.56	109.77	52.72	90.99	57.15	88.65	48.30
IOF	A2S64	70.84	17.09	110.55	76.41	89.39	81.34	88.65	67.23
IOF	A2*S54	60.44	9.37	111.34	55.99	90.99	60.31	89.47	50.97
IOF	A2*S544	57.13	9.32	110.49	55.64	90.99	60.12	81.37	48.63
IOF	A2*S545	54.12	9.23	109.82	55.20	89.63	59.43	76.43	46.95
IOF	A2*S5450	65.43	9.37	133.25	59.95	94.81	61.33	105.25	54.71
IOF	A2*S5475	67.35	9.37	149.29	62.36	98.62	62.30	117.35	57.17
IOF	A2*S54100	72.89	9.37	163.16	64.19	102.44	63.22	127.56	59.01
IOF	A2*S64	76.84	18.90	116.2	82.13	89.39	84.87	89.47	70.26
IOF	A2*S644	68.43	18.72	115.32	81.44	89.39	84.54	81.37	65.91
IOF	A2*S645	66.55	18.55	114.62	80.83	88.05	83.46	76.43	63.05

Table A2. Numerical and predicted resistances for hat sections under IOF loading

Specimen		Numerical result		EN1993-1-3		SEI/ASCE 8-02		Proposal	
		$R_{u,num}$ (kN)	$M_{c,num}$ (kNm)	$R_{w,Rd}$ (kN)	$R_{WC\text{-}BD}$ (kN)	$R_{w,Rd}$ (kN)	$R_{WC\text{-}BD}$ (kN)	$R_{w,Rd}$ (kN)	$R_{WC\text{-}BD}$ (kN)
IOF	A1S71	4.11	0.98	5.52	4.09	5.30	4.75	5.22	3.91
IOF	A1S81	5.35	2.53	5.52	5.45	4.82	6.06	5.22	5.19
IOF	A1S91	4.48	1.42	5.52	4.67	5.14	5.39	5.22	4.47
IOF	A1*S71	4.15	0.99	5.52	4.10	5.30	4.77	5.24	3.94
IOF	A1*S714	3.84	0.97	5.34	3.99	4.94	4.55	4.83	3.72
IOF	A1*S715	3.61	0.96	5.18	3.90	4.57	4.32	4.60	3.59
IOF	A1*S7150	4.76	0.99	6.86	4.64	6.09	5.14	6.54	4.47
IOF	A1*S7175	5.22	0.99	7.89	4.99	7.10	5.56	7.53	4.82
IOF	A1*S71100	6.19	0.99	8.75	5.26	8.34	5.99	8.37	5.08
IOF	A1*S81	5.46	2.50	5.52	5.43	4.82	6.05	5.24	5.19
IOF	A1*S91	4.58	1.44	5.52	4.70	5.14	5.42	5.24	4.50
IOF	A1*S914	4.21	1.41	5.34	4.56	4.79	5.14	4.83	4.23
IOF	A1*S915	4.18	1.44	5.18	4.50	4.44	4.92	4.60	4.11
IOF	A1*S9150	5.21	1.44	6.86	5.42	5.90	5.93	6.54	5.21
IOF	A1*S9175	5.73	1.44	7.89	5.91	6.89	6.51	7.53	5.69
IOF	A1*S91100	6.85	1.44	8.75	6.28	8.09	7.13	8.37	6.06
IOF	A2S71	4.29	1.00	5.52	4.12	5.30	4.80	5.29	3.98
IOF	A2S81	5.75	2.53	5.52	5.44	4.82	6.06	5.29	5.24
IOF	A2S91	4.78	1.45	5.52	4.71	5.14	5.44	5.29	4.54
IOF	A2*S71	4.62	1.03	5.52	4.14	5.30	4.85	5.38	4.06
IOF	A2*S714	4.23	1.02	5.34	4.04	4.94	4.64	5.00	3.88
IOF	A2*S715	4.09	1.01	5.18	3.96	4.57	4.42	4.81	3.77
IOF	A2*S7150	5.06	1.03	6.86	4.69	6.09	5.24	6.71	4.62
IOF	A2*S7175	5.49	1.03	7.89	5.04	7.10	5.67	7.73	4.98
IOF	A2*S71100	6.35	1.03	8.75	5.31	8.34	6.12	8.59	5.25
IOF	A2*S81	6.24	2.58	5.52	5.45	4.82	6.09	5.38	5.33
IOF	A2*S91	5.20	1.49	5.52	4.72	5.14	5.49	5.38	4.63
IOF	A2*S914	4.81	1.48	5.34	4.61	4.79	5.22	5.00	4.40
IOF	A2*S915	4.80	1.48	5.18	4.52	4.44	4.96	4.81	4.28
IOF	A2*S9150	5.59	1.49	6.86	5.45	5.90	6.00	6.71	5.36
IOF	A2*S9175	6.02	1.49	7.89	5.94	6.89	6.60	7.73	5.86
IOF	A2*S91100	7.08	1.49	8.75	6.32	8.09	7.24	8.59	6.24
IOF	A1S72	14.34	2.44	19.41	12.29	22.59	15.39	22.22	12.98
IOF	A1S82	19.45	7.22	19.41	18.26	21.61	24.16	22.22	20.06
IOF	A1S92	16.21	3.92	19.41	15.11	22.26	19.52	22.22	16.25
IOF	A1*S72	14.57	2.48	19.41	12.40	22.59	15.54	22.27	13.11
IOF	A1*S724	13.10	2.43	18.99	12.14	21.89	15.15	19.90	12.29
IOF	A1*S725	12.18	2.43	18.62	12.03	21.19	14.96	18.36	11.81
IOF	A1*S7250	16.14	2.48	23.43	13.60	24.40	16.05	26.99	14.29
IOF	A1*S7275	17.14	2.48	26.51	14.37	26.22	16.52	30.61	15.05
IOF	A1*S72100	18.91	2.48	29.11	14.95	28.04	16.95	33.67	15.60
IOF	A1*S82	19.85	7.25	19.41	18.29	21.61	24.19	22.27	20.11
IOF	A1*S92	16.51	3.96	19.41	15.18	22.26	19.62	22.27	16.35
IOF	A1*S924	14.59	3.93	18.99	14.93	21.57	19.22	19.90	15.23
IOF	A1*S925	13.45	3.89	18.62	14.70	20.88	18.80	18.36	14.44
IOF	A1*S9250	18.97	3.96	23.43	17.00	24.05	20.45	26.99	18.22
IOF	A1*S9275	20.73	3.96	26.51	18.23	25.84	21.23	30.61	19.46
IOF	A1*S92100	24.66	3.96	29.11	19.18	27.64	21.96	33.67	20.40
IOF	A2S72	15.03	2.55	19.41	12.56	22.59	15.80	22.37	13.34
IOF	A2S82	20.70	7.44	19.41	18.39	21.61	24.37	22.37	20.32
IOF	A2S92	17.08	4.06	19.41	15.30	22.26	19.83	22.37	16.55
IOF	A2*S72	15.87	2.68	19.41	12.77	22.59	16.24	22.56	13.74
IOF	A2*S724	14.37	2.65	18.99	12.56	21.89	15.92	20.25	12.95
IOF	A2*S725	13.33	2.66	18.62	12.46	21.19	15.72	18.77	12.48
IOF	A2*S7250	17.15	2.68	23.43	14.04	24.40	16.80	27.35	15.02
IOF	A2*S7275	18.17	2.68	26.51	14.87	26.22	17.31	31.02	15.85
IOF	A2*S72100	20.20	2.68	29.11	15.49	28.04	17.78	34.11	16.46
IOF	A2*S82	22.77	7.72	19.41	18.49	21.61	24.65	22.56	20.66
IOF	A2*S92	18.25	4.27	19.41	15.50	22.26	20.28	22.56	16.98
IOF	A2*S924	16.33	4.25	18.99	15.26	21.57	19.88	20.25	15.86
IOF	A2*S925	15.85	4.24	18.62	15.06	20.88	19.51	18.77	15.11
IOF	A2*S9250	20.42	4.27	23.43	17.41	24.05	21.18	27.35	18.98
IOF	A2*S9275	22.01	4.27	26.51	18.71	25.84	22.01	31.02	20.32
IOF	A2*S92100	25.48	4.27	29.11	19.70	27.64	22.79	34.11	21.33

Table A3. Numerical and predicted resistances for SHS/RHS under EOF loading

Specimen		Numerical result	EN1993-1-3	SEI/ASCE 8-02	Proposal*
		$R_{u,\,num}$ (kN)	$R_{w,\,Rd}$ (kN)	$R_{w,\,Rd}$ (kN)	$R_{w,\,Rd}$ (kN)
EOF	A1*S1250	19.86	10.33	10.63	10.21
EOF	A1*S5275	21.78	10.33	11.70	10.42
EOF	A1*S52100	23.22	10.33	12.76	10.60
EOF	A1*S521002	18.52	10.33	9.57	9.94
EOF	A1*S62	17.75	10.33	8.96	9.94
EOF	A1*S624	15.90	10.11	8.24	9.68
EOF	A1*S625	14.31	9.91	7.51	9.72
EOF	A2S62	18.62	10.33	8.96	10.10
EOF	A2*S5250	22.18	10.33	10.64	10.68
EOF	A2*S5275	24.96	10.33	11.70	10.90
EOF	A2*S52100	26.72	10.33	12.76	11.08
EOF	A2*S521002	21.41	10.33	9.57	10.40
EOF	A2*S62	20.16	10.33	8.96	10.40
EOF	A2*S624	18.03	10.11	8.24	10.27
EOF	A2*S625	16.16	9.91	7.51	10.47
EOF	A1S64	53.58	38.14	39.59	46.13
EOF	A1*S5450	61.18	38.14	43.23	47.23
EOF	A1*S5475	69.13	38.14	45.64	47.93
EOF	A1*S54100	75.74	38.14	48.04	48.52
EOF	A1*S541002	60.04	38.14	40.83	46.32
EOF	A1*S64	55.36	38.14	39.59	46.32
EOF	A1*S644	52.02	37.58	39.59	42.52
EOF	A1*S645	48.77	37.08	38.10	40.31
EOF	A2S64	58.64	38.14	39.59	46.68
EOF	A2*S5450	69.58	38.14	43.23	48.29
EOF	A2*S5475	80.44	38.14	45.64	49.01
EOF	A2*S54100	89.25	38.14	48.04	49.62
EOF	A2*S541002	75.02	38.14	40.83	47.36
EOF	A2*S64	64.80	38.14	39.59	47.36
EOF	A2*S644	61.16	37.58	39.59	43.79
EOF	A2*S645	57.30	37.08	38.10	41.83

*After readjustment

Table A4. Numerical and predicted resistances for hat sections under EOF loading

Specimen		Numerical result	EN1993-1-3	SEI/ASCE 8-02	Proposal*
		$R_{u,\,num}$ (kN)	$R_{w,\,Rd}$ (kN)	$R_{w,\,Rd}$ (kN)	$R_{w,\,Rd}$ (kN)
EOF	A1S81	3.13	2.15	1.58	1.99
EOF	A1*S81	3.17	2.15	1.58	2.01
EOF	A1*S814	2.87	2.08	1.24	2.01
EOF	A1*S815	2.66	2.02	1.13	2.07
EOF	A1*S9140	4.16	2.15	2.00	2.06
EOF	A1*S9150	4.79	2.15	2.14	2.09
EOF	A2S81	3.25	2.15	1.58	2.05
EOF	A2*S81	3.40	2.15	1.58	2.12
EOF	A2*S814	3.12	2.08	1.24	2.15
EOF	A2*S815	2.92	2.02	1.13	2.26
EOF	A2*S9140	4.35	2.15	2.00	2.17
EOF	A2*S9150	4.97	2.15	2.14	2.20
EOF	A1S82	11.93	7.85	8.96	8.91
EOF	A1*S82	12.13	7.85	8.96	8.95
EOF	A1*S824	10.86	7.68	8.24	8.33
EOF	A1*S825	9.83	7.53	7.51	7.99
EOF	A1*S9240	16.61	7.85	10.08	9.11
EOF	A1*S9250	19.45	7.85	10.50	9.20
EOF	A2S82	12.53	7.85	8.96	9.04
EOF	A2*S82	13.33	7.85	8.96	9.19
EOF	A2*S824	12.13	7.68	8.24	8.62
EOF	A2*S825	10.89	7.53	7.51	8.35
EOF	A2*S9240	17.91	7.85	10.08	9.35
EOF	A2*S9250	20.77	7.85	10.50	9.44

*After readjustment